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Experimental Study on Spouted Bed Hydrodynamics for Oil Shale Semi-Coke

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Abstract

A cold-state spouted bed for oil shale semi-coke was designed and set up. The effect of different static bed height and particle size on the spouting pressure drop was studied. The results indicated that the spouted bed drop increased with increasing of static bed height and increasing of particle size at the same superficial air velocity. The experiential correlation equation of the minimum spouting velocity proposed by Mathur and Gishler was quoted for calculation with a correlation coefficient 0.983. The values obtained were in good agreement with the experimental data.

Keywords: oil shale semi-coke; spouted bed; spouting pressure drop; minimum spouting velocity

1. Introduction

Oil shale, as a sedimentary rock, can generate shale oil and other pyrolysis products including dry distillation gas, semi-coke and shale ash after pyrolyzed. Shale oil has similar properties to the petroleum which can produce product oil by subsequent processing and also be used directly as fuel oil. The dry distillation gas is able to provide heat required for pyrolysis itself and a part of surplus dry distillation gas is utilized as by-product. The shale ash can be filled mines and be applied to make Building Materials like cement, brick, ceramisite, etc [1]. Oil shale is used as an auxiliary energy source of petroleum and most used for combustion for electric power generation and refining shale oil by retorting in industry [2-4]. Semi-coke of oil shale can be directly combusted to generate power, and the shale ash left is an ideal heat carrier for oil shale retort. Oil shale semi-coke owns high ash content and low heat value. According to

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the requirement of solid heat carrier, How to burn semi-coke effectively and get hot ash are the key technologies to the design of oil shale retorting process.

A spouted bed consists of relatively coarse solid particles partly filling a cylindrical vessel, which is provided with a small, centrally located inlet aperture in its (usually conical) base (Figure 1). A fluid injected through this inlet at velocities beyond a certain minimum value will cause a stream of particles to rise rapidly in a hollow central core (the "spout") to form a fountain above the peripheral bed level. The particles rain back onto the annular region between the spout and the wall, and thereafter travel slowly under gravity in a dense phase with some countercurrent percolation of fluid, establishing a systematic cyclic pattern of particle movement (the spout, annulus and fountain have clearly different properties) [5-7]. The spouted bed developed from mid 1950s, which is suitable for handing coarse particles (particle size d_p>1), belongs to the fluidization technology [8-10]. It was initially used to dry wheat, and it has attracted attention for a number of remarkably varied operations, like granulation, drying, smashing of solution, coating of strong coherent or massive particles, suspending liquid, coal combustion and gasification, oil cracking, etc. Compared with the random complex particle flow in most fluidized bed, the agitation of particles in the spouted bed is caused by a stable axial jet with more regularity. If bed temperature was higher than 870℃ and fines captured in primary cyclone were recycled to the bed, Lim et al. (1988) found that the spouted bed combustor efficiency could be over 90%, even for high ash solid fuels [11, 12]. Pressure drop and the minimum spouting velocity are the important parameters for the design and operation of spouted bed. The pressure drop determines power consumption serviceability and the minimum spouting velocity is the key parameter to operate.

The oil shale semi-coke sample from Huadian was adopted to study the spouted bed flow characteristics. The relationships of the spouting pressure drop and particle size, as wel as and bed height are determined, which will provide the reference for the spouted bed combustion technics of oil shale semi-coke.

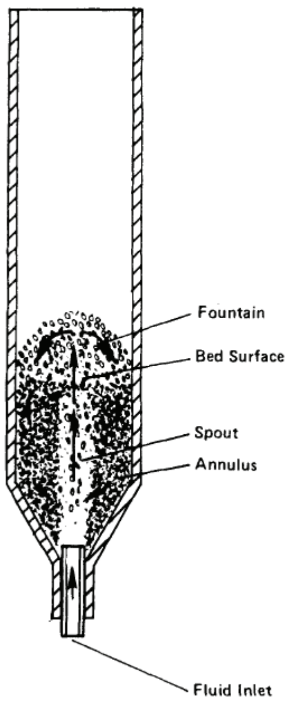


Figure 1. Schematic diagram of a spouted bed (section)

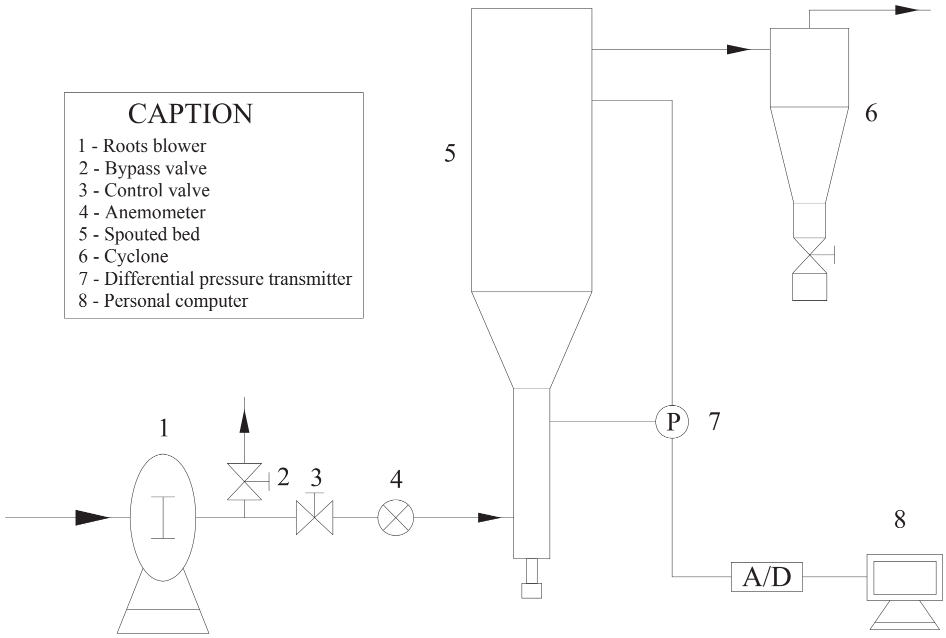


Figure 2. Schematic of spouted bed combustion system

2. Experimental

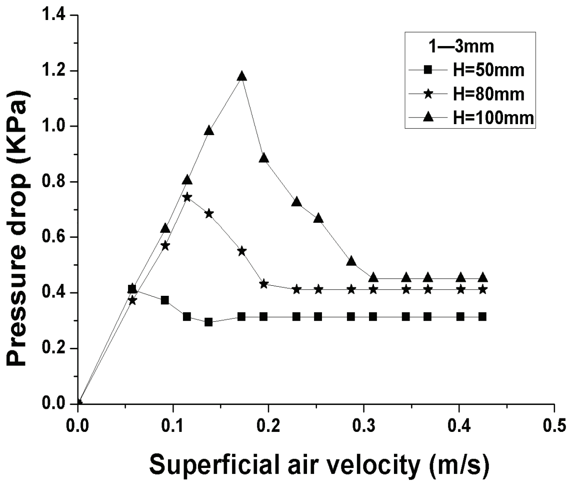
The experiments were carried out in the spouted bed device designed independently. The main part of the reactor is a carbon steel semi-cylindrical spouted bed with glass observation windows. The internal diameter of the cylindrical section is 0.15m and gas nozzle with diameter of 0.05m is used. The conical bases have an internal angle of 60°. The schematic diagram of the experimental set-up is shown in Fig.2. The experimental samples are Huadian oil shale semi-cokes with particle size of 1-3 and 3-5mm (density of 1630 kg/m^3, sphericity of 0.55). Experiments conducted in normal temperature, atmospheric pressure.

A certain amount of oil shale semi-coke particles sieved were added into the spouted bed as bed materials and the static bed height was measured by a ruler. Air, as spouting gas, provided from a Roots blower entered the bed through the nozzle at the bottom. It could make particles in the bed stably spout by adjusting air flow through changing the opening of control valve and bypass valve. Ultimately the air into the bed passed through cyclone and discharged into the atmosphere. Gas velocity obtained by digital anemometer and pressure drop (between the inlet of gas nozzle and outlet of gas out- flowing from the spouted bed) measured by differential pressure transmitter. Pressure signals were logged into a computer via an A/D converter with 12-bit resolution.

3. Results and discussion

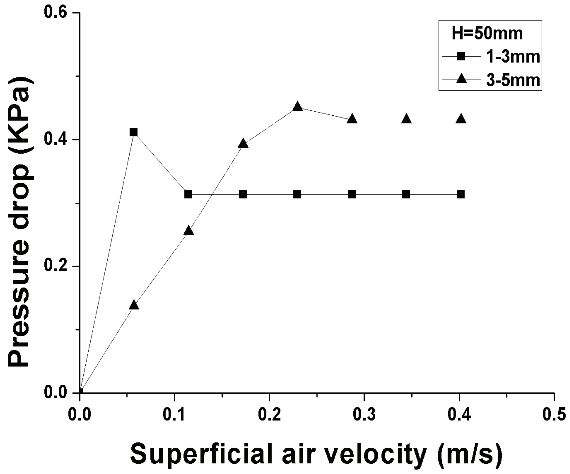
3.1 Effect of different static bed height

When the superficial air velocity increases from zero, jet zone is formed at the inlet first and particles begin circulating in it, that is to say, particles are carried to the top from the jet zone. The jet zone scales up with sustained increasing air velocity until it penetrates the fixed bed surface. Bed pressure drop is from zero to maximum value accordingly in this process. The maximum pressure drop as changing from fixed bed to spouted bed is called Maximum Spouted Bed Pressure Drop. Since then, the pressure drop decreases with continuing to increase air velocity and the jet zone gradually formed a steady spouting zone. The spouted bed complete spouting, which has steady flow structure of three zones, is set up in the bed at last. Once the steady spouted bed forming, the pressure drop will not increase as continuing to increasing air velocity. Therefore, that is the operating pressure drop. Fig.3 shows the spouting pressure drop change versus superficial air velocity. It is seen that the spouting pressure drop increases with the increasing of the static bed height at the same superficial air velocity. This is because the bed resistance increases with the static bed increasing, leading to the increasing of the spouting pressure drop. In addition, the minimum spouting velocity is proportional to the bed height, which coincides with some related literatures reported when the bed height no more than the conical bottom height [13, 14].



Particle size: 1-3mm, H - static bed height

Figure 3. Pressure drop variation with superficial velocity of air



H-static bed height

Figure 4. Pressure drop variation with superficial velocity of air

3.2 Effect of different particle size

Fig.4 represents the relationship between the spouting pressure drop and superficial air velocity. Fig.4 shows that the spouting pressure drop rises when the particle size is increased at the same superficial air velocity. This is because the resistance of the annular region decreases with the particle size increasing at the same static bed height. As a result, the amount of air entering into the spouting area decreases and the spouting pressure drop increases. It also can be concluded from experiment that the particle size has a great influence on the minimum spouting velocity, so that the effect of particle size on the minimum spouting velocity should be considered when wide screening particle size oil shale semi-cokes are used for burning in the spouted bed combustor. Meanwhile, it should consider the theoretical combustion air volume, residence time of material burning and other factors to obtain the best optimization of air velocity.

3.3 The minimum spouting velocity correlation

The minimum spouting velocity corresponds to the onset of spouting of particles in the spouted bed when particles start to be suspended and move upward in the spouting region. Researches have shown that the minimum spouting velocity is not only related to the characteristics of the fluid and solid, but also to the initial spouted bed height and to the spouted bed geometry. So far, it is lack of reliable general correlation to calculate the minimum spouting velocity because of complexity of the problem.

In this study, the experiential correlation equation of the minimum spouting velocity derived from dimensional analysis in relatively deep beds with H/D≥1.3 by Mathur and Gishler was quoted [15]:

$$U_{ms} = \left(\frac{d_p}{D}\right)\left(\frac{D_i}{D}\right)^{1/3}\sqrt{\frac{2gH\left(\rho_p - \rho\right)}{\rho}}$$

Where, U_{ms} is the minimum spouting velocity, m/s; d_p is the average particle diameter, m; D is the column diameter, m; D_i is gas inlet diameter, m; H is the static spouted bed height, m; ρ_p is the density of the solid, kg/m^3; ρ is the density of the liquid, kg/m^3. What is more, d_p is geometric mean particle diameter for narrow screening spherical or nearly spherical particle, equivalent specific surface diameter for Materials of mixed mean particle, volume equivalent particle diameter for non-spherical particle，and Ellipse minor axis for prolate ellipsoid particle.

From Fig.5, it can be found that the values calculated by the correlation are in good agreement with the measured values. The correlation coefficient is 0.983 and the deviation is limited in ±10%.

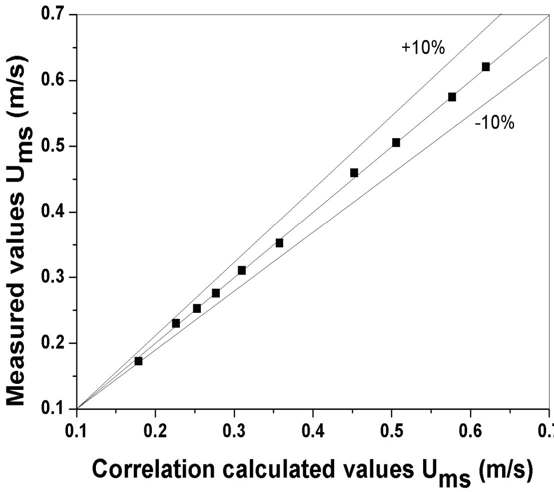


Figure 5. Comparison between measured values and correlation calculated values

4. Conclusions

(1) At the same superficial air velocity, the spouting pressure drop is increased with the increasing of the static bed height and particle size.

(2) The values calculated by the empirical correlation has a good agreement with measured values with the correlation coefficient of 0.983 and the deviation less than±10%, therefore, they have high reliability and application value.

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